A Data Simulation Study of the NGST Multi-Object Spectrograph

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Abstract

There are many options for the design of a multi-object spectrograph (MOS) for NGST. Some proposals suggest reflective or transmissive slit-masks in the focal plane. Others promote the use of fibre bundles to feed the light to the spectrograph. Although there are many successful multiplexing instruments for ground-based astronomy, there is a lack of experience in multi-object techniques for space telescopes and so the advantages and disadvantages of the different options must be investigated. The HST gives the best idea of what to expect for deep imaging and spectroscopy with NGST, but the extrapolation is non-trivial. The NGST will be in a very different orbit, have a much larger aperture, and have more advanced detectors. This study accounts for these differences as well as simulating the operation of a multiplexing spectrograph in order to investigate the NGST MOS.

The HST NICMOS deep fields are used to generate artificial NGST NIR fields. Spectra are synthesized for objects in these fields by employing available photometric redshift data, template galaxy spectra, and model background spectra. Direct imaging with simulated filters and detectors can also be performed on these fields. In addition, a simulated NGST spectrograph can be run in a multiplexing mode and, thereby, create a virtual NGST MOS. An Integral Field Unit (IFU) is also simulated, operating as an image slicer. Results suggest that S/N ~10 spectroscopy of H(AB)-magnitude 30 galaxies will be possible with NGST. Although the NGST field is crowded at these depths, roughly 50 1.0” x 0.2” slits per square-arcminute are possible with no spectral overlap at R=100. A fibre-fed spectrograph is advantageous for resolutions approaching R=5000 to avoid overlapping spectra.

1.0 Introduction

There are several options for the design of a MOS for NGST. They differ in their means of directing the light of the sources into the spectrograph. However, all configurations will require the determination of an optimal slit size. At the suggestion of David Crampton, a numerical simulation was designed to determine the effect of slit size on the S/N of an extracted spectrum of a galaxy.

The original test program was designed to study a single galaxy with a single slit of variable size. An archival B-band image of M51 was scaled both in pixel sampling and brightness to roughly match its appearance if imaged by NGST. Furthermore, this scaling could be altered to simulate its appearance if it were at different redshifts and for different exposure lengths. A template spectrum of an Sb galaxy was obtained and shifted according to the user-defined redshift. By scaling the brightness of the image by the resulting SED for many wavebands, an artificial spectrum at each pixel was determined. A rectangular aperture could be selected and placed on this “spectral-image”. By applying a spectral-response curve for a broadband filter as well as the quantum efficiency for a given detector, direct imaging of this field could be simulated. The light passing through could also be dispersed to create the output of an artificial spectrograph. A region of interest could be selected from this spectrum to yield an extracted spectrum. Finally, the S/N of this extracted spectrum was output. By varying the size of the aperture the user could determine the optimal S/N. In order to determine the background light a model based on that described by Wheelock (1994) was employed. This was suggested by Simon Morris and will be discussed further below. Finally, the simulation was made even more realistic by including the effects of detector gain, readout and shot noise, and by performing the integration as a co-add of 1000 second exposures.

These investigations suggest that even an L* galaxy such as M51 would not be detected in imaging by NGST if it were at $z>2$. This was surprising at first but others (e.g. Burgarella et al. 1998) have obtained similar results. It was also clear that S/N=10 low-resolution spectroscopy of galaxies with apparent magnitudes much fainter than H(AB) =30 would require exposure times greater than 10^6 seconds.

The goal of this investigation was to determine the optimal size of slits and possibly determine advantages and disadvantages to the various mechanisms for directing the light into the spectrograph. The initial investigation was inadequate because it did not simulate a realistic galaxy field as seen with the NGST. It also had only one slit. It was clear that although the technique of simulating a spectrograph was sound, a better means of generating artificial NGST fields was needed. Furthermore, a means of expanding this single slit model to simulate a multiplexed observation would need to be devised. The method of generating artificial NGST deep fields is discussed in Section 2. The operation of the resulting simulation including a multiplexing capability is discussed in Section 3. The results are discussed in Section 4.

2.0 Generating Artificial NGST Deep Fields

To realistically simulate deep spectroscopy for NGST one first needs a realistic NGST deep field. One might begin from “first principle” and generate an entirely artificial galaxy field given an expected luminosity function, size-magnitude relation, etc.It could even include galaxy evolution. But, this approach is problematic because there will be no way to know what galaxy evolution NGST will see until NGST can observe it. An alternative is to take the deepest known NIR observations - those of the HST NICMOS deep fields and extrapolate them. This idea is similar to the method of Hubble Deep Field “cloning” by Bouwens et al. (1997). However, the goal of their method is mainly to alter the redshift distribution of the original HST WFPC2 deep fields without increasing the depth of the exposures.

The basic method adopted here is to add many new fainter galaxies to the observed deep fields - in effect, greatly increasing the depth of exposures. The simulation uses images from the HST NICMOS Deep Field South (HDFS) and photometric redshift survey data on the galaxies in this field to generate artificial NGST fields. It utilizes a model for the background illumination consisting of a scattered and thermal component of the zodiacal light. It has template spectra of four different galaxy types, E/S0, Sbc, Scd, and Irr which are redshifted according to a photometric redshift catalog. The simulated galaxies are generated by spreading the H-band HST NICMOS image over the range of 1 to 5 microns according to the expected SEDs.

Since the galaxies in the original HST field are under-sampled and noisy, in a further refinement they were replaced by artificial galaxies. These retain the spectral classification, brightness, redshift, and size of the original galaxies but these properties are used to generate highly over-sampled artificial galaxy images. These morphological templates correspond to the four galaxy spectral types and are based on a two component model of an r^{1/4}-bulge and exponential-disk. The disk is augmented with spiral structures, star-formation regions, etc., based on scaling an image of the brightest low-redshift spiral galaxy available in the HDFS. The resulting template galaxies are formed with user-supplied values for bulge and disk radii, and bulge-to-total ratios. In the results discussed here, however, the original HDF galaxies were cloned into the NGST field without the complication of deriving morphological templates (the latter were necessary in a detailed study of imaging with NGST. Using galaxy image templates instead of direct clones of HDF galaxies in the spectroscopic studies did not affect the results and it is mentioned here only for completeness).

The simulation then generates the artificial NGST field by taking faint galaxies from the HDF field (say, H(AB) >25), shifting them fainter by a few magnitudes and to a factor higher in redshift, making them smaller, and then putting them back into the field in randomized locations and rotations. In fact, the resulting spatial distribution of galaxies in the field is not entirely random. The galaxies are preferentially put down (according to a normal distribution with a specified `correlation length') next to randomly chosen original galaxies. The correlation length here is the FWHM (in arcseconds) of the normal distribution. This simulates the projected spatial `clumpiness' of a real correlation function of galaxies. The simulation actually puts several `clones' back in the field for each faint galaxy to mimic the steep increase in source counts at these magnitudes.

The background is calculated using a model that includes both a scattered and thermal component of the zodiacal light; the scattered component is multiplied by the observed NIR solar spectrum to simulate the effects of solar absorption features.

One difficulty encountered with our simulation method occurs with overlapping galaxies. The masks used to separate galaxies are circular and the galaxies can have very small separations. In the case of extreme overlap, the average magnitude is used in the updated catalog. The spectral types may be mixed under these circumstances. That is, a portion of a galaxy might have an SED that is intermediate between the different overlapping types.

3.0 A Virtual NGST MOS

Additional refinements to the original simulated imager and spectrograph were made to enable more detailed analyses of the projects outlined in the Design Reference Mission. The filters and gratings were included with specified efficiency curves. The detector characteristics were also expanded to include size, pixel-scale, well-depth, gain, quantum-efficiency, dark current, readout and shot-noise. The user can select a particular galaxy for study from the artificial NGST deep field and perform direct imaging or spectroscopy on it. The slit size, grating resolution, and exposure duration can be input as parameters. Given values for detector size, pixel-scale, etc., the simulation outputs what the imager or spectrograph would actually record on the detector. The user can choose a region for spectral extraction and the simulation performs the reduction and extracts the spectrum. Diagnostic numbers are also output, such as the H-band magnitude and radius of the galaxy as well as S/N and resolution of the extracted spectra.

A means of simulating image-slicing was also devised. This is achieved by scanning across an approximately 2.0” x 4.0” region centered on the selected galaxy and performing slit-spectroscopy at, say, 20 positions as described above. The resulting spectra are reformatted to a single slit and recorded by the detector. Also recorded is the region covered by spectra on the detector - called the `footprint' - which provides statistics on the efficiency of detector coverage.

Finally, a multiplexing mode was included. The number and size of spectrograph slits can be specified and they are placed on galaxies of a given magnitude selected at random. Four different focal plane mask configurations are simulated: a micro-mirror mask, a reconfigurable fibre-fed system, a slit-mask composed of sliding bands, and a micro-machined shutter mask. The latter three are comparable to those described in the Canadian NGST MOS studies. The simulation operates by `blocking out' regions of the focal plane of the different mask configurations as each available position is used.
As in the image-slicing mode, the resulting spectra on the detector and their footprints are recorded.

This method of performing virtual imaging, image-slicing, and multiplexed spectroscopic surveys with NGST was written as an IDL tool. It is included in a larger simulation of NGST instrumentation (along with a virtual Visible Imager (VI)) called `NGST VI/MOS' (Steinbring 1999b). The goal of the investigation discussed here was to determine the optimal size of slits and compare the various slit-mask designs. The imaging mode for the MOS was included to provide a direct comparison with the VI. This was investigated by the author for the Canadian NGST VI study and will not be discussed further here. The results are available in Steinbring (1999a). The image-slicing IFU was another proposed mode for the Canadian MOS and, thus, was included for completeness.

A copy of the NGST VI/MOS software is available from the author. See also http://astrowww.phys.uvic.ca/~steinb/ for a web-based tour of NGST VI/MOS.

4.0 Discussion/Results

The main goal of this work was to determine the S/N of extracted spectra as a function of galaxy brightness and spectrograph slit size. This is a straightforward experiment for NGST VI/MOS and was investigated using `virtual observing runs'. Basically, the programs suggested by Lilly et al. (1998) in their Design Reference Mission (DRM) proposal were carried out with the simulation. These call for deep (10^6 second) exposures of galaxy fields. They propose low resolution (R=100) spectroscopy of H(AB)-magnitude 30-31 galaxies to extend spectroscopic redshift surveys to the faintest limits possible. They also propose higher resolution (R =5000) spectroscopy of brighter (H(AB)-magnitude 26-28) galaxies to determine characteristics of galaxy formation and evolution.

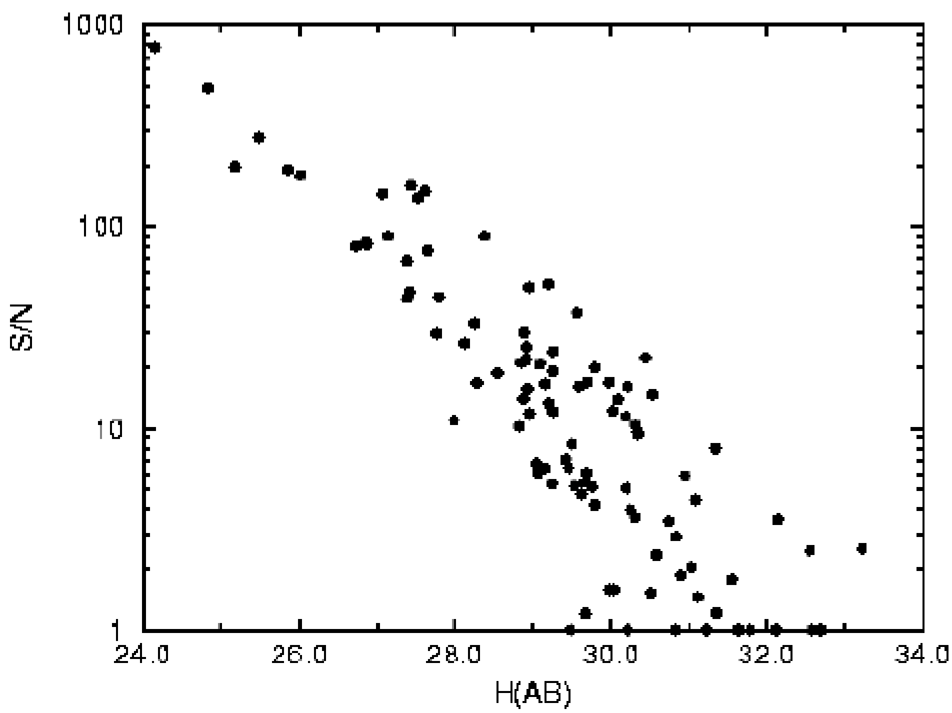

Figure 1: A plot of S/N versus H(AB) magnitudes for galaxies in the HST Deep Field South as observed with NGST MOS. Slits were 0\farcs2 wide and the delivered resolution was R=100. The results are essentially identical for slits 0.5 arcseonds wide.

A realistic artificial field was generated. It was purposefully made to be `clumpy'. That is, the correlation-length parameter was set to 3.0”. This value was chosen because it is the smallest value for which severe overlapping of galaxies is not a problem. Setting this value to, say 0.5”, will cause almost all cloned galaxies to overlap another galaxy. Setting the value to 25” is essentially a random distribution of galaxies on the sky. The simulation was run in multiplex mode with various slit widths and lengths. The spectrograph had 50 slits for the 50 x 50 square-arcsecond field. This was based on the assumption of approximately 200 slits for a 2 x 2 square-arcminute field for NGST. The simulation placed slits on the first 50 H(AB)-magnitude 30-31 galaxies selected at random, performed spectroscopy and returned the S/N.

It quickly became clear that slit width is not a critical factor. Faint galaxies (H(AB)-magnitude 30-31) are small - with half-light radii of only about 0.1”. The small galaxy sizes determine the resolution of the spectra. As long as the slit is not much wider than about 1.0” the increase in background light does not adversely affect the S/N of R=100 spectra. This is assuming that no other galaxy finds itself into the slit of the galaxy of interest. It is found, however, that this is often the case if the slit is wider than 0.5”. Thus, the size of the slit is effectively limited by the galaxy density of the fields. These simulations also suggest that background subtraction is very effective in space. For co-adds of 1000 second exposures a calibration slit placed on the `sky' will provide excellent subtraction of the background. This is why the slit width (in the absence of crowding by other galaxies) can be as large as 1.0”. These results suggest that S/N ~10 spectroscopy of H(AB)-magnitude 30 galaxies will be possible with NGST. Although the NGST field is crowded at these depths, roughly 50 1.0” x 0.2” slits per square-arcminute are possible with no spectral overlap.

The second DRM proposal that was investigated was that of surveying relatively bright (H(AB)-magnitude 26-28) galaxies at higher resolution (R~5000). It was clear that there would be no problem concerning S/N for these galaxies. Typical S/N are in the hundreds, if not a decade more than that, for exposures of 10^6 seconds. These brighter galaxies generally have fairly large apparent sizes, typically being larger than 1.0” across. A 0.2” slit will not have a problem with contamination by other galaxies while still providing ample light for the spectrograph. One concern, however, is that high resolution spectroscopy requires a lot of `real estate' on the detector. Each spectrum would be at least 1.0” wide, and dispersed along 10000 pixels on the detector. Thus even if the blue end of the spectra began at the leading edge of the detector 50 galaxies would completely cover the detector with spectra. In this case, a fibre-fed spectrograph would be very advantageous for resolutions approaching R=5000. A slit-mask would always have overlapping spectra.

Most of our analyses indicate that the scientific return for microslits, mechanical slits and fibre slitlets are similar for low resolution spectra. For R=3000, the reformatting of he spectra by the fibres becomes important.

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NGST VI/MOS website: http://astrowww.phys.uvic.ca/~steinb/